The outer layers of the Sun

As noted before, the sun is the only star for which we can directly observe the detailed nature of surface structures.
The layers of the outer atmosphere of the Sun that we see in visible light (so between 400-900 nm) are called the *photosphere*.
This is the region of the Sun's atmosphere where the temperature and density are such that most of the radiation is emitted at visible wavelengths.
The depth of the photosphere is only about 400 km, so very small compared to $R_\odot = 6.96 \times 10^5$ km
The photosphere is heated from below by energy streaming from the solar interior, and T(r) decreases as you travel outwards through the photosphere.

Limb darkening

This property can be observed directly, and is known as limb darkening.
If you look closely at pictures of the sun you see that outermost projected regions of the Sun - the limb of the Sun - appear slightly darker than the main disc of the Sun.
This is because we are looking at emission from different depths of the Sun - when we look at the centre we are looking more deeply into the Sun.
Since material is hotter, it radiates more energy than the cooler material we observe when we view the limb, and so it appears brighter.
This means that the limb is only 40% as bright as the centre of the Solar disc.

The Photosphere & beyond

When observed in visible light, it looks like the photosphere has a relatively sharp boundary, and is the last layer of of the Sun.
In fact when we observe the Sun in a total solar eclipse, we see the Sun has 2 further outer layers - the *Chromosphere* and *Corona*.

The Chromosphere

A relatively thin 'sphere of colour' which glow pink in photographs.
The Chromosphere has a low density (10^{-4} of the photosphere) and initially has a somewhat lower temperature than the photosphere ($\sim$4400 K).
Spectroscopy reveals that the spectrum of the chromosphere does not show absorption lines, but numerous sharp emission lines.
The pinkish colour of the Chromosphere comes from the very strong Hα line at 656.3 nm.
The element helium was also first discovered in the spectrum of the Chromosphere in 1868, before the gas was isolated on the Earth.
Analysis of spectra shows that the temperature actually rises with height in this region, reaching about 25000 K at the top of the chromosphere.
High resolution images show that there are vertical spikes permeating the chromosphere - these are rising jets of gas called *Spicules*.
These are time variable, typically lasting $\sim$15 minutes, and rise at $\sim$20 km/s.
They may reach several thousand km in height before collapsing and fading away.
Typically there are about 300,000 spicules, covering 1% of the surface of the Sun.

The Photosphere & Spicules

Closer examination of the photosphere shows it has a rather blotchy appearance; this is known as *granulation.*
Each granular *cell* has a rough diameter of ~1000 km, and each cell is surrounded by a somewhat darker boundary.
This corresponds to a difference of about ~300 K in temperature.

Granulation

The granulation is caused by *convection cells* in the photosphere.
Hotter gas from lower levels rises upwards in the granules, cools, spills over the edge and sinks.
Time series show that the granules form and disappear individually in cycles lasting a few minutes.
Over the whole surface there may be ~4 million granules, each typically covering an area of 10^6 km^2
Superimposed on these are larger convection cells called *supergranules.* These can be up to 35,000 km across.
Doppler data show these rise at ~0.4 km/s (1/10th that of granules) and last about a day.
Spicules are usually seen directly above the edge of supergranules (note that gas is rising in spicules and falling at edge of supergranules).
It is believed that the Sun's powerful magnetic field is depositing energy in these regions allowing gas to rise.

The Solar Corona

Also seen during a solar eclipse is the last outer atmospheric region of the Sun - the solar corona.
The Solar Corona is not seen to be a smooth spherical shell of gas, but shows numerous streamers, whose shapes and timsecales vary (although typically they last for days - weeks).
The Corona has an emission line spectrum from optical to X-ray energies produced by transitions of highly ionised atoms, such as Fe XIII at 530.3 nm.
Analysis shows that the gas temperature reaches very high temperatures in the Corona - 2×10^6 K or higher - and that the rise is very sudden from the top of the Chromosphere, through a very thin transition region.
The Solar Corona is not 'hot' in the usual sense of the word, since it contains very little thermal energy due to its very low density of ~10^{11} atoms/m^3.
By comparison the photosphere has a density of ~10^{23} atoms/m^3 and the Earth's atmosphere a density of ~10^{25} atoms/m^3.
The low density also explains why it is so faint - approximately a million times fainter than the photosphere, or comparable to the full moon. Therefore the disc of the sun must be hidden (e.g. during an eclipse) for it to be visible.
The high temperature of the Corona means large ion velocities are generated, leading to an outflow called the *Solar Wind.*
The solar wind ejects about 10^9 kg/sec of material from the Sun.
It consists of electrons, protons, HeIII (so just the nuclei) and heavier element nuclei/atoms.
When they reach and interact with the Earth's magnetic field at the polar regions they give rise to the Earth's Aurorae.
The high temperature of the Corona, plus the high energy collisions (which also heat the gas) give rise to intense X-ray emission.
Recent space missions have and continue to observe the Corona/stellar wind in UV and X-rays.
A good example of this is shown in Fig. 18-18, where the Sun is observed in the UV.

Here the denser/higher temperature regions appear bright and vice versa.
Images like these show dark patches - called Coronal Holes which are almost devoid of coronal material. It is through these regions of low density gas that particles can most easily escape from the Sun - hence the Coronal Holes are the "corridors" through which the Solar Wind escapes from the Sun.

The Sun, Magnetic Fields & Sunspots

The temperature of the Solar Corona was found in the 1930s, but it is only now that we think we have some idea of the heating mechanism - the energy contained in the Sun's magnetic field.
Some of the most striking features of the Sun at visible wavelengths are **Sunspots**, which appear as dark patches on the photosphere.
(Observations show that granules, supergranules, spicules and the solar wind occur all the time, and are representative of the **Quiet Sun**.
Other features occur ∼periodically, and include massive eruptions and regions of concentrated magnetic field (indicated by sunspots) - these are representative of the **Active Sun**.*)*

Sunspots

The basic characteristics of Sunspots are:

- Irregular shaped dark regions
- Sometimes occur in isolation, sometimes in groups
- Sizes vary - typically few 1000 km in size (so comparable to Earth...)
- Each spot has a dark central core - **umbra** and a brighter border region - **penumbra**
- Temp(umbra)=4300K
- Temp(penumbra)=5000K
- From Stefan-Boltzmann: Flux(umbra)/Flux(penumbra)=0.55

Sunspots & variability

Sunspots are *variable...*

- Individual sunspots last for a few hours to a few months.
- Individual sunspots can be tracked as they rotate around the Sun. Rotation rates differ from the pole to the equator. This is known as differential rotation.
- Period of rotation of the equator is 25 days
- Period of rotation near the pole is 35 days
- Average number of susnspots varies *cyclically*, with a period of 11 years
- Location in latitude of sunspots also varies with the 11 yr cycle. At the beginning of each new cycle spots first appear ±30° from the equator. In subsequent years the location of spots gets closer to the equator until the end of the cycle when nearly all the spots lie on the equator.

Sunspots & magnetism

What causes this cyclic behaviour, and how do sunspots arise?
The basic question was answered when it was revealed that sunspots are associated with intense magnetic fields.
This is observed via the **Zeeman effect**.
The Zeeman effect is due to quantum mechanics (specifically spin orbit coupling which we *won't look at...*) and causes spectral lines of a single energy to split into two lines of slightly different energies in the presence of a magnetic field.
Typical sunspots have magnetic fields 5000× that of Earth at the poles.